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**Studies of Fracture Processes in Cement-Based Materials
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Damage and failure mechanisms in cement-based materials such as concrete are difficult to comprehend due to the heterogeneous microstructure. Experimental analysis of damage localization and failure has traditionally been a compromise between low resolution three-dimensional techniques, and high resolution surface techniques. In this research program, two emerging experimental techniques, x-ray microtomography and computer vision, were combined toward problems of damage and failure of concrete. X-ray microtomography produces a high resolution three dimensional picture of internal damage evolution, while speed computer vision allows us to quantitatively evaluate surface cracking characteristics at variable loading rates under multiple stress states. The primary focus of the work under this grant was to explore the feasibility of these two techniques for applications to shock physics. Preliminary results showed that high resolution (micron scale) scans of internal structure can be made at multiple levels of damage using the experimental setup developed for microtomography. Additional results quantified cracking and damage localization as a function of material composition using the computer vision system developed at Northwestern. Combining the results from both techniques allows us to establish relationships that will form the basis for the next generation of material fracture and damage models.

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STUDIES OF FRACTURE PROCESSES IN CEMENT-BASED MATERIALS UNDER COMPRESSION WITH MICROTOMOGRAPHY AND COMPUTER VISION

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Introduction

The primary focus of the work performed under this grant was to explore the feasibility of two emerging experimental techniques for applications to shock physics. The motivation for the use of these advanced techniques is based in the fact that in order to advance our understanding of material failure processes we must be able to link performance properties to *observable microstructural features*. As described in more detail below, the two techniques used for this research provide unique "windows" into material microstructure. When the observations of materials made from these techniques are combined with the measured mechanical response, a true link can be made between microstructure and properties. The data generated by these experiments can then be used as a basis for advanced material constitutive models.

Background

Computer Vision

Digital Image Correlation (DIC) is a computer vision technique that can be used to measure displacement fields on the surface of an object. This measurement requires two digital images obtained from different loading stages (strains). The fundamental and well documented concept of DIC is based on the recognition of two small sub-image areas extracted from each of the two images. Each sub-image represents a distinct state of strain on the specimen surface. The random surface pattern on the sample permits any point to be identified by the light intensity pattern of the sub-image surrounding it. Given a suitable pattern searching algorithm, sub-image taken from a reference image can be matched with an extracted sub-image from another image selected for measurement. Displacements are defined as the relative distance between the original and the best matching sub-image. If several such displacement points can be identified, a surface displacement map can be rendered.

Microtomography

X-ray microtomography (XMT) is a technique by which the internal structure of a material may be determined from maps of its x-ray adsorbility. Three dimensional maps are reconstructed from hundreds of through transmission radiographs of the sample taken from different angles. Microtomography is similar in practice to conventional medical CAT-scans. The primary differences are the x-ray source and detector. Microtomography uses synchrotron radiation for the x-ray source and a high resolution x-ray detector. A spatial resolution of about $2 \mu\text{m}$ is possible, although $13 \mu\text{m}$ to $6 \mu\text{m}$ pixels were used in the preliminary experiments described here. The data that results from a scan is a series of images which represent cross-sectional "slices" through the material. The advantage of microtomography for investigations of damage in cement-based materials is its ability to measure internal structure in three dimensions at high resolution.

It should be noted that an extremely important issue related to both these methods, is that no single experimental technique is adequate to answer all questions that arise over damage accumulation and fracture. XMT provides extremely high quality three dimensional data, but the samples and experimental conditions are somewhat limited. DIC deformation mapping is easily adaptable to a wide variety of applications, however,

it provides surface measurements only. Thus, the motivation for combining the two techniques is for an optimized experimental program.

Summary of Work

Parallel tests were conducted on samples of cement and mortar using computer vision and microtomography. The samples consisted of plain cement paste, fine mortar and concrete for the computer vision experiments, and fine mortar for the microtomography experiments.

Micromotography

A simple experimental apparatus was used for scanning samples while under load. This apparatus allowed multiple scans to be made on a single specimen at different load levels. The resulting internal damage could then be correlated directly with bulk material properties such as load and deformation. Image analysis routines have been developed to extract three dimensional crack area from the cross-sectional image data. The initial image analysis approach used was very straight forward, but somewhat flawed. In a single slice, the total length of a crack was measured. Then the measured crack lengths for all the slices of a particular scan are added to determine a crack area. Crack areas for scans taken at different levels of strain are then compared to the bulk load and deformation response of the specimen. The flaw in this approach is that each individual slice is considered separately from an image analysis standpoint. A better approach and the focus of continuing work is to treat the data as a complete three dimensional data set, and do all image analysis in three dimensions.

Preliminary results indicate internal crack growth can clearly be observed in three dimensions at multiple levels of damage in the same specimen. A fine mortar specimen at three different load steps is shown in Figure 1. Three dimensional renderings of tomographic data are shown in Figure 2. These figures clearly illustrate some of the features critical to the fracture behavior of the material, such as crack branching and bridging. It should be noted that due to limitations of the x-ray beam from the synchrotron, investigations are limited to small samples. The cylinders shown in Figures 1 and 2 are 4 mm in diameter. Thus any conclusions from the experiments must be qualified.

A particular focus of the experiments conducted under this award was to consider the

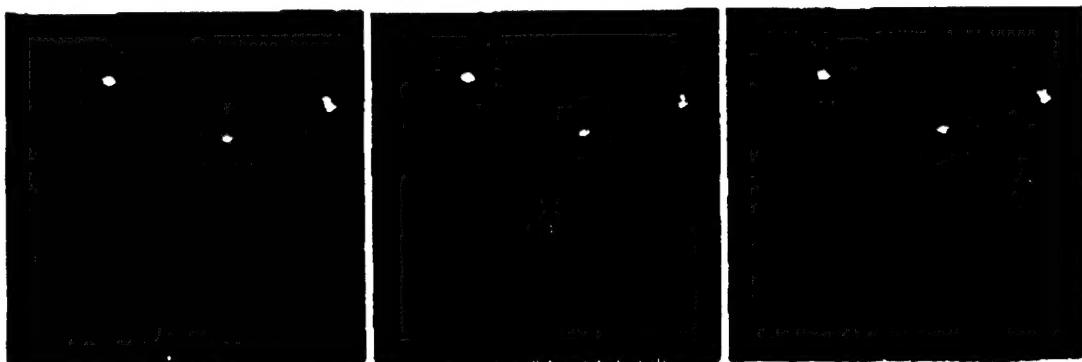


Figure 1. Tomographic scan of specimen at three levels of damage

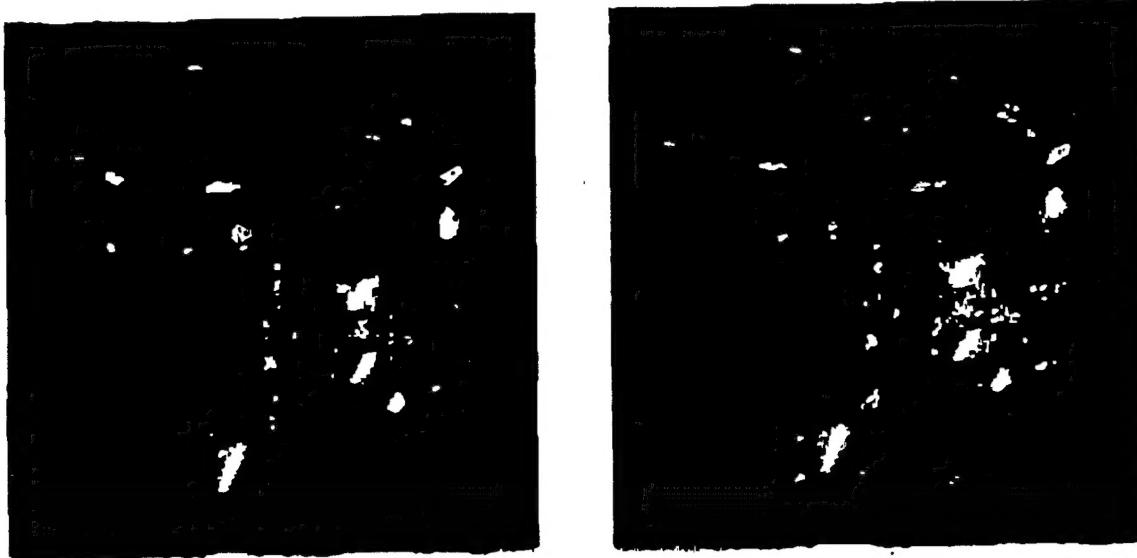


Figure 2. Three dimensional renderings of tomographic data taken at two different levels of damage.

relationship between crack measures made on the specimen surface, and measurements made on the specimen interior. This relationship is significant because it may establish when surface measurements are sufficient, and when complete three dimensional measurements are necessary. Because of the experimental tradeoffs between surface and internal measurements described above, this investigation will be particularly important in reconciling future microtomography and computer vision measurements.

In order to examine this relationship, some image analysis routines were developed. Specifically, using 2 dimensional cross sectional slices, a routine was developed to determine the intersection between an internal crack, and the specimen surface. The way this is done is that the number of pixels that are identified as *both* specimen boundary and crack are counted for each slice. These pixel totals are then summed and converted to a length.

A comparison of work of load versus internal crack area and work of load versus external crack length was made for a mortar specimen. Plots of both are shown in Figure 3. As

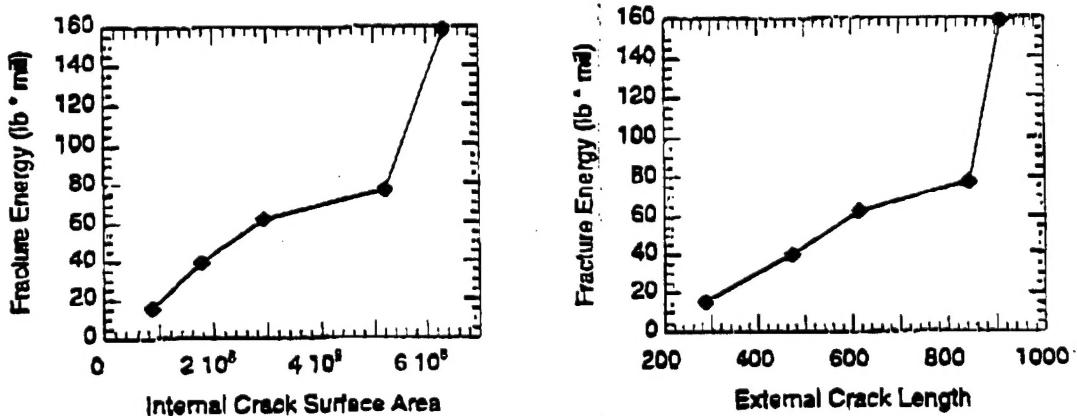


Figure 3. Internal crack surface area and external crack length versus fracture energy

can be seen in these figures, both damage measures (internal crack area and surface crack length) give similar curves. Although this result must be confirmed with additional experimentation, a preliminary conclusion is that surface measurements may be used to infer the level of internal damage.

Computer Vision

In previous work, a digital charge-coupled device (CCD) or camera with the high resolution of 1280x1024 pixels, a real-time image processing board, and computer programs were combined to capture specimen images during compression loading tests. In a series of experiments, the barrel effect due to the end shear confinement was clearly visualized in the deformation maps created by this method. When the end constraints were removed by inserting friction-reducing materials, this barrel effect was removed. This demonstrated the ability of this technique to measure surface deformation with a meaningful specimen size for a test conducted with a sensitive large-capacity hydraulic testing machine.

With this system, the factor limiting the sensitivity of measurement is the accuracy of the measuring technique. This is determined by the accuracy of the digital image correlation algorithm, which returns displacement in units of pixels. This is converted to physical distance by multiplying it by the ratio of the physical dimension imaged and the number of pixels used to describe that dimension. To increase the accuracy of physical measurement the camera was moved closer to the specimen, reducing the distance each pixel covers. However, this also reduced the amount of specimen covered by a single image. To record the full surface of the specimen, a traveling mechanism for the camera using a precision motorized stage was developed to facilitate recording multiple images which could later be combined.

This modified experimental system consists of three parts: a digitally controlled closed-loop servo-hydraulic loading system, a digital camera and analysis hardware, and a traveling mechanism. The diagram in Figure 5 is a schematic of the experimental setup. In practice, the specimen area was divided into 56 (8x7) subregions only one of which was covered by the digital camera's field of view at one time (Figure 5). To capture all 56 images, the camera system moved over the whole specimen area using the two (x- and y-axis) motorized stages.

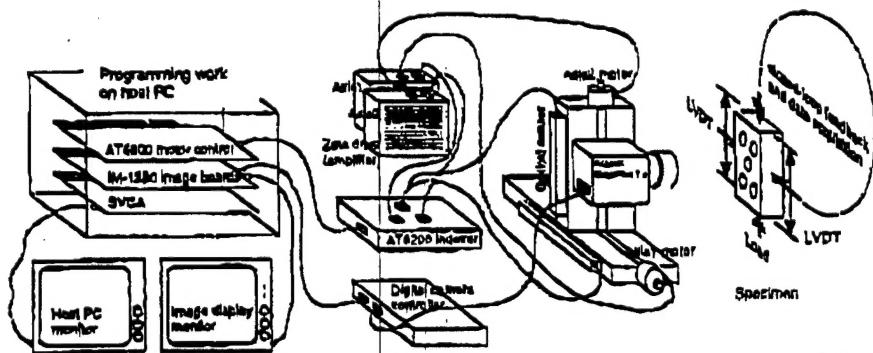


Figure 4. Hardware diagram for subregion scanning computer vision

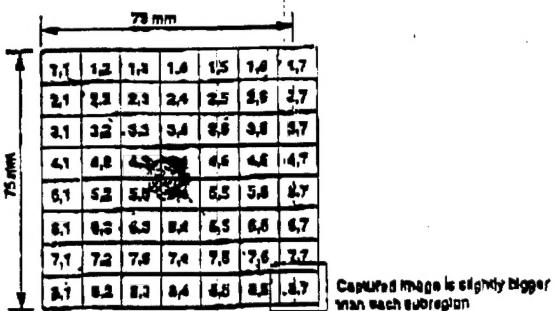


Figure 5. The specimen is divided into 8x7 subregion.

The specimen examined was loaded in compression using a combination of axial and lateral displacement as a feedback signal. During the 5-minute period required for a complete scan of the surface, this feedback signal was kept constant to restrain further crack propagation. Even though load drops during the scanning period due to relaxation, the axial and lateral deformations remain constant. This ensures that the final image composed from the 8x7 individual images represents the same deformation level throughout and that the displacement contours obtained are suitable for our purpose.

The magnification factor of the recorded images, which corresponds to the distance separating the camera and specimen, was calculated using two images taken from two different stage locations. The image displacement was obtained from DIC matching and compared with the magnitude of the translation of the stages. The ratio of the two is the magnification factor is slightly different but approximately 11 in both the x- and y-direction for the 75x75mm specimens tested. The average and standard deviation of the measurement errors with the current experimental system were approximately 0.06 and 0.04 pixels, respectively. They correspond to 0.65 and 0.45 μm , respectively, for the magnification factors used in this research.

Conclusions

The X-ray microtomography and computer vision techniques were found to be an exceptional combination for examining relationships between material microstructure and fracture properties of concrete and cement-based materials. Preliminary results showed that high-resolution (micron scale) scans of internal structure can be made at multiple levels of damage using the experimental setup developed for microtomography. Through the development of the subregion scanning computer vision technique, maps of surface deformation of similar sensitivity can be produced to describe the external structure as damage occurs. Combining the results from *both* techniques allows us to establish relationships that will form the basis for the next generation of material fracture and damage models.

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